# Public transport of tomorrow: zero emissions vehicles including electric buses and buses with fuel cell range extenders

Michał Sierszyński[1], Bartłomiej Walczak[1], Adam Piotrowski[1], Michał Pikuła[1],

*[1]Solaris Bus & Coach SA, Research & Development Department, Obornicka 46, Bolechowo-Osiedle 62-005 Owińska, Poland, bartlomiej.walczak@solarisbus.com, michal.pikula@solarisbus.com, michal.sierszynski@solarisbus.com, adam.piotrowski@solarisbus.com*

## Abstract

Care for the environment and thus increasingly restrictive emission standards forced the changes approach to the public transport. Many cities are looking for the way to improve air quality for their citizens. One of the elements to achieve this is environmental friendly public transport based on low-emission vehicles. Among the pro-ecological solutions that are able to replace diesel buses are battery/electric buses or buses equipped with a hydrogen fuel cell range extenders. However these kind of vehicles still need to challenge few issues: eg. higher price, weight, they offer the most important advantage which is zero emission in place of exploitation.

Aim of this work is to show the features of electric buses referenced to the requirements of public transport. Among the others this paper will focus on the solution with hydrogen range extender as a promising zero emission option for long daily operation. This document presents current status of bus alternative solutions and their potential for future development.

Keywords: *fuel cell, electric buses, electric buses with fuel cell range extender*

## 1 Introduction

### 1.1 Environmental requirements for public transport

Introduced in recent years Euro 6 emission standard significantly reduced the amount of harmful substances emitted by buses with combustion engines. In face of the strict requirements such as the "EU Directive on Ambient Air Quality and Cleaner Air for Europe" bus manufacturers are obliged to search for clean technologies. It is expected that in near future there will be a significant increase in zero-emission vehicles in Europe due to the fact that diesel engines have their own boundaries for further improvement in reducing toxic gases and pollutions.

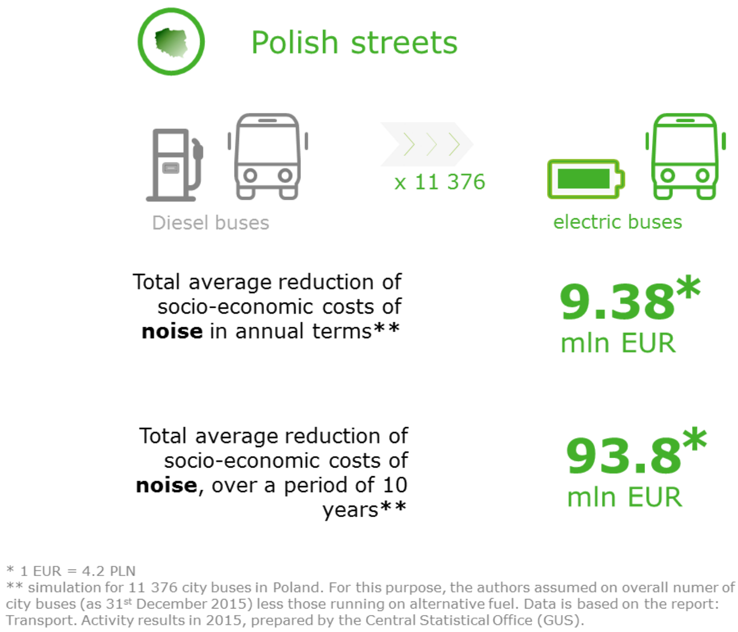



Figure 1 The impact of replacing diesel or petrol buses with electric ones, made by Solaris, on Polish streets [1]

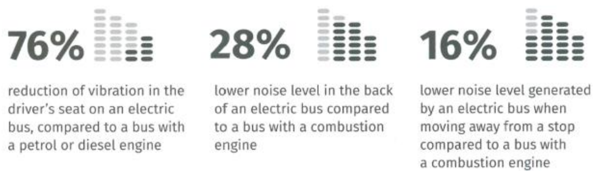



Figure 2 Reduced noise and vibration levels in electric buses [1]

Not only emissions of harmful substances to the atmosphere at the place of use of the vehicle is an important environmental aspect. It is also important to take care of the environment by reducing noise and vibration caused by public transport vehicles. The transfer of vibration to the external environment and noise is limited by the approval regulations that each vehicle must comply with. They define, for example, the maximum permissible vehicle gross weight, the maximum axle loads and noise values that can`t be exceeded under certain conditions. Bus manufacturers take care about health, safety and comfort of drivers and passengers and typically, in newly developed constructions and propulsion systems they getting better values than required by homologation. New construction and systems reduce impact of both vibration and noise. As presented on Figure 2, for example electric buses have much lower level of vibration in the driver' seat (76%), lower noise (28%) in the back of the vehicle, as well as lower noise (16%) is generated while bus is moving away from a stop in comparison to a bus with a combustion engine [1].

### 1.2 Technical requirements for zero emission vehicles

For many years internal combustion engines (ICE) were dominant in automotive. This situation has determined the current line timetables, daily services and maintenance. In order to meet the requirements of the public transport operators (PTOs), bus must be a good alternative not only in environmental aspects, but also in other areas.

Regardless, it is passenger car or public transport vehicle there can be seen a lot of similarities. Performance, design or even brand are not so important for the customer as reliability, environmental impact or costs.

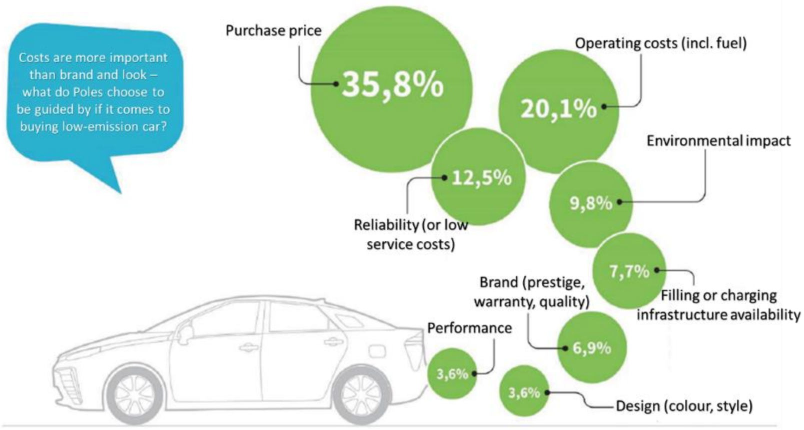



Figure 3 Survey by SW Research for ORPA.pl, June 2015 [3]

PTO's, whose fleets are dominated by Diesel buses, are frequently asking bus manufacturers about nearly the same features as presented on Figure 3 which applies to passenger cars. Those questions are mostly about purchase price, energy consumption (operating costs) and total cost of ownership. The performance of electric buses, how they work and how does the infrastructure should look like also appear in the inquiries, but they are not treated in the initial phase by the PTO`s as the key to the decision to launch electromobility activities.

## 2 Alternative solutions for diesel buses

Electric bus seems to be the best alternative for Diesel bus that ensure zero emissions in the cities. However, typical Diesel bus drive a minimum of 350 km on one refueling even in the most difficult winter conditions with fully operational heating, so it is not easy to replace them with other solution. In the case of zero-emission in place of operation electric bus, energy need to be provide not only for drive train but also for on-board systems and heating / air conditioning systems which are one of the most significant factors, which determines single-charge range. The impact of HVAC system (**H**eating, **V**entilation and **A**ir **C**onditioning is higher if the commercial speed is slower and operating temperature range is wider (especially when winters are cold). Some operators, in favour to extend single-charge range, chose to use Diesel heating, however that bus is no longer a zero-emission bus at the area of operation.

Basing on real-operation data from Polish operators, including Warsaw Public Transport Operator (MZA Warszawa), there are some months with low energy consumption (~1.1 kWh/km), while HVAC has low power demand and most of the energy is consumed by traction but we see also very high consumption during winter months. Heating system was has the significant influence on energy consumption. Total energy consumption shown on Figure 4 was calculated as energy consumed by the electric drivetrain with auxiliaries and oil consumed by Diesel heating system by MZA Warszawa [2].

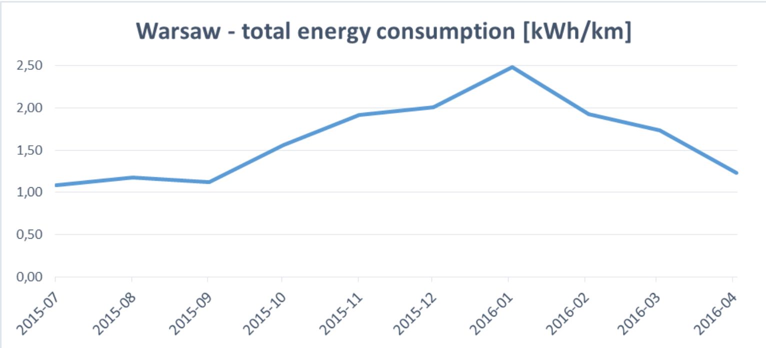



Figure 4 Warsaw – total energy consumption [kWh/km] [2]

Figure 5 and Figure 6 present power distribution of components having the biggest influence on the energy consumption. Power demand for the drivetrain, air compressor, 24 V installation and power steering is almost the same for wide range of temperature. While ambient temperature is -30°C, the heating system requires over 50% of total power demand to provide sufficient comfort in the passenger’s compartment.

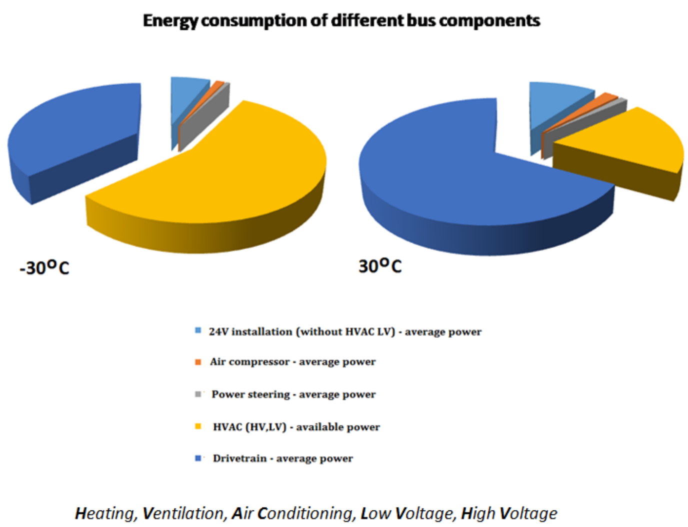
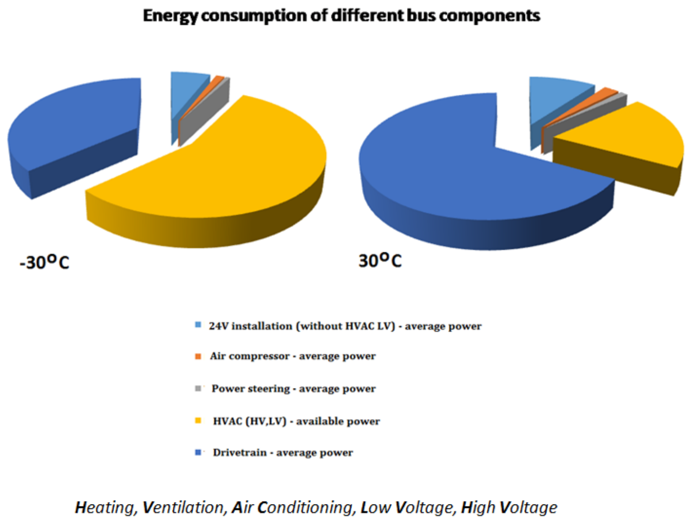



Figure 5 Energy consumption of different bus components by high and low temperatures. [4]




As it can be seen on Figure 6, range of electric bus with new 240 kWh batteries varies between 90 kilometres even up to 180 km for standard easy-urban conditions, depending mostly on HVAC system's power demand. If considered batteries' end of life (as 85% of initial capacity) single charge range is between 75 and 150 km.

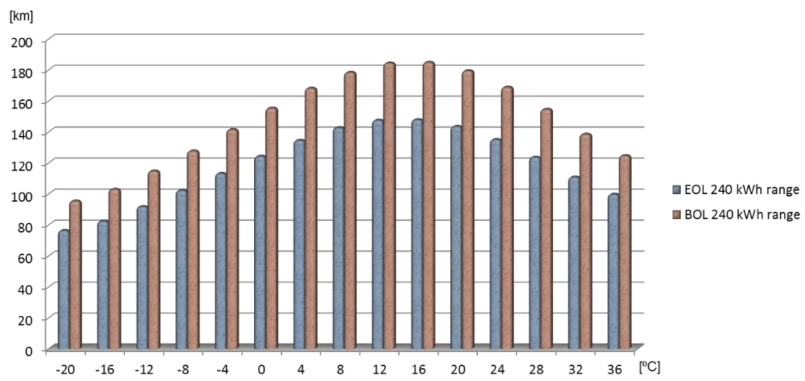



Figure 6. Influence of HVAC system energy consumption on bus single charge range - an example based on SORT 2 conditions and HVAC for 22°C interior temperature [4]

## 2.1 Overnight charged buses

The idea of using buses in overnight charging schedule come out from the current customer habits, the flexibility of routes and the lack of infrastructure for charging buses in the city. Current battery technology does not allow buses to be charged only at night and could operate in all weather conditions throughout the entire day. For this case batteries need to be recharged also during the day. Currently in overnight charged buses battery capacity achieved values over 200 kWh. They can drive long distance with low frequency of charging, depending on commercial speed, auxiliaries and power demand etc. Dominant battery technologies in this case are LFP and NMC. However, this solution has one fairly serious defect: mass of batteries limits total number of passengers. Each kWh of energy in batteries is an extra ~10 kg or more, so 7-8 kWh more energy in batteries, what means that bus can take one passenger less.

Currently buses with big batteries are mostly recommended for peak operation (rush hours) or to operate at suburban lines. Rush hours are one of most demanding challenges for electric bus operators. Usually they occur two times per day: in the morning and in the late afternoon.

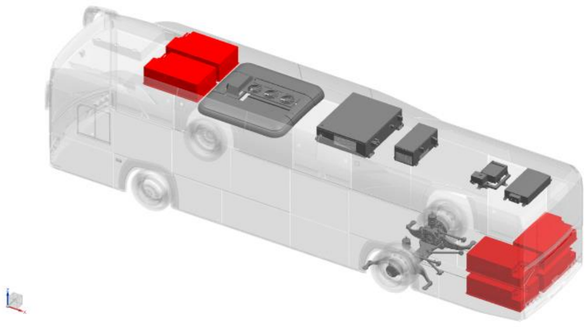
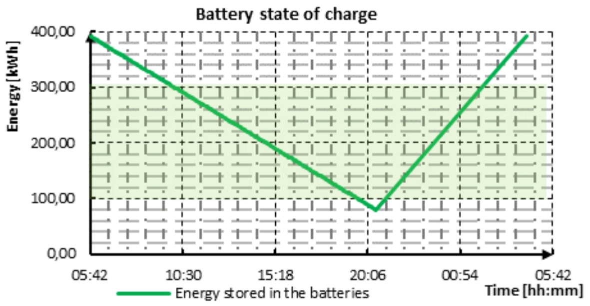


Figure 7 Overnight charged bus - concept with 6 battery packs (240 kWh) [4]

As already mention above not only drive train affects the power and energy consumption of the bus. While average commercial speed is high, influence of HVAC systems becomes smaller and vehicle have more energy for drive train. This Paper consider an example case of customer which require 238 km on a single charge. To accord with Total Cost of Ownership (TCO), it is extremely important to choose batteries properly (reducing number of battery exchanges during useful life), hereby battery depth of discharge should not be higher than 80% of available capacity and 80% of 80% of initial capacity should be considered as the end of life. Results of theoretical battery capacity (signed with the “*” sign) are presented below:

Table 1 12 meter bus – simulation based on real drive cycle and stop points (suburban line). [4]

| **12 meter bus – simulation based on real drive cycle and stop points (suburban line)** | |
|---|---|
| Battery capacity | 400 kWh* |
| Technology type | LFP |
| Chargers at the terminals | --- |
| Depot charger | 40 kW |
| Battery state of charge |   |
| Charging points | --- |
| Number of charging on the line | 0 |

| | |
|---|---|
| Energy consumption | 1,31 kWh/km |
| Consumed energy | 312,9 kWh |
| Covered distance | 238,6 km |
| Average charging time on the line | 00:00:00 hh:mm:ss |
| Average charging time at the depot | 08:01:00 hh:mm:ss |
| Night layover time | 09:14:00 hh:mm:ss |
| Operating time | 14:46:00 hh:mm:ss |

Bus was able to cover 238,6 km with average commercial speed of 25 km/h in worst climate conditions with average energy consumption of 1.31 kWh/km. As the minimum battery capacity 400 kWh was considered (for mixed-urban or heavy-urban conditions required capacity might be even 50-80% higher). For this moment such kind of system for sub-urban conditions would have approximately mass of 4 tonnes.

Currently on the market are several solutions, which allow to use such amount of the energy in lower weight (approximately 3 tonnes), however high energy density is usually at the expense of the battery lifetime – even 2-3 years instead of 5-8 years of useful life. Useful life is a specific amount of time until bus will not be able to cover required distance in each conditions).

## 2.2 Opportunity charged buses

Buses which are used for opportunity charging are equipped with smaller batteries (usually <100 kWh) than in the case of buses charged at night, which means that total mass of batteries is smaller comparing to standard electric buses. Natural consequence of lower battery mass is bigger passenger capacity. It this case it is possible to compete with Diesel buses. The disadvantage is that they need to be charged even 20 times per day and they need special infrastructure on the line. That requires high power charging, which can achieve 450 kW. Because of that LTO chemistry is most commonly used.

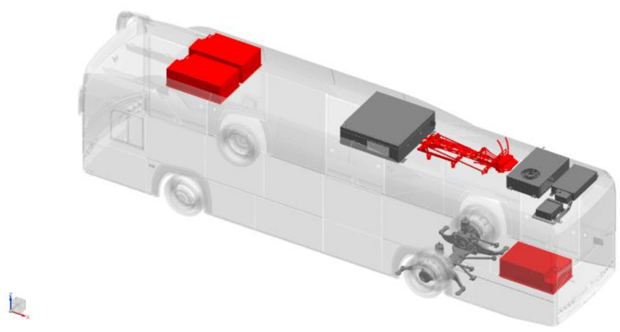


Figure 8 Opportunity charged bus - concept with 3 battery packs and pantograph charging system [4]

High Power batteries are best choice for operators, who are covering long mileages every day but the single trip is relatively small. Fast charging allows them to fill consumed energy in very short time period, even less than 5 minutes regardless the weather conditions. Batteries are well adjusted to line requirements and they are able to cover one loop without charging in case of emergency or charger fault in worst calculated conditions – with HVAC system on.

## 2.3 Electric buses with fuel cell range extender

Size of batteries is usually smaller than in opportunity charged buses but there are additional elements such as fuel cell stack, auxiliary fuel cell devices and hydrogen storage system. Hydrogen can significantly extend the range to even 400 km or more on single fuelling. Because of that, they seem to be the best alternative for diesel buses for long daily mileage and hilly roads where conventional electric buses rapidly lose their range. This type of bus connects advantages of fuel cell and batteries. During normal drive fuel cell covers power demand of drivetrain, batteries cover peak power demands and absorb energy form  regenerative breaking.

Fuel cell is an element which converts energy stored in hydrogen to electricity.  The efficiency of fuel cell as well as other electrical components (such as converters) or battery c-rate are major factors, which have direct influence how much energy will be stored in batteries or transferred into wheels. The key advantage of this element is that during entire process only waste products are heat and steam.

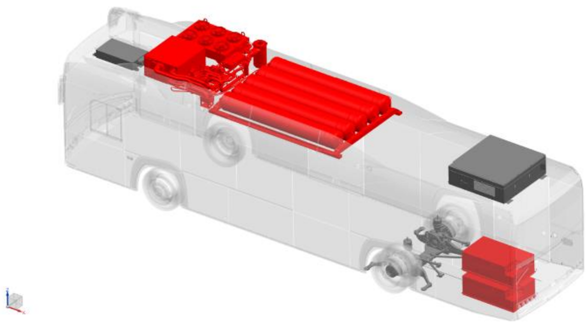


Figure 9 Electric bus with fuel cell range extender - concept [4]

Usually hydrogen is stored on buses roof in type 3 cylindrical tanks. For this vehicles 350 Bar at 15°C is maximum working pressure (Regulation (EC) No 79/2009). Hydrogen has high lower heating value of 120 kJ/kg [5] which means that taking into account fuel cell and converters efficiencies, same amount of energy as in above mentioned battery bus (Figure 7) can be stored in ~16kg of hydrogen. In this case of requirement of 400 kWh (as described in opportunity charged bus chapter) can be covered with 26,7kg of hydrogen. Analogically bus equipped with ~34 kg storage system can store 510 kWh of energy.

Among the concepts for the energy storage systems in hydrogen buses it can be found both batteries and supercapacitors. Supercapacitors are not able to store big amount of energy, however can be used during big peak power demands. Development of hydrogen buses is also connected with battery technology. The most useful is one that provides stock of energy and allow big charging and discharging power for short period of time. LTO technology, same as in opportunity charging buses seems to be the best choice for this purpose.

# 3 Development of electric vehicle solutions for long daily mileage

The base configuration of the electric bus, regardless of the case discussed in the previous section, is the same. As shown in Figure 10, the basic structure can be divided into 4 groups:

- Energy storage system
- External power supply
- Auxiliaries
- Drive train

In case of hydrogen range extender buses the external power supply group is supported by onboard generation power supply group which consist fuel cell stack.

Base algorithms related to the drive system control are the same but significant differences are found in the general algorithms that control the power flows in the system. The most complicated situation is with hydrogen-powered range extenders, because in this case there are two sources of energy (fuel cell and batteries) that need to be managed in a skillful way.

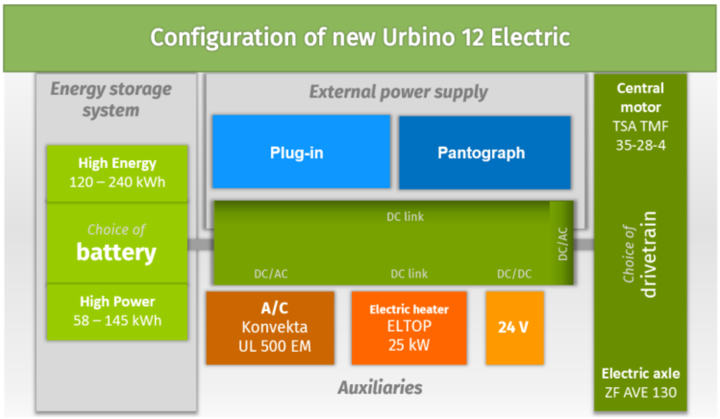



Figure 10 Configuration of new Urbino 12 Electric [4]

By comparing the different parameters of buses with alternative propulsion to the diesel bus, the most important of them were identified as descriptive data and collected and presented in Figure 11.

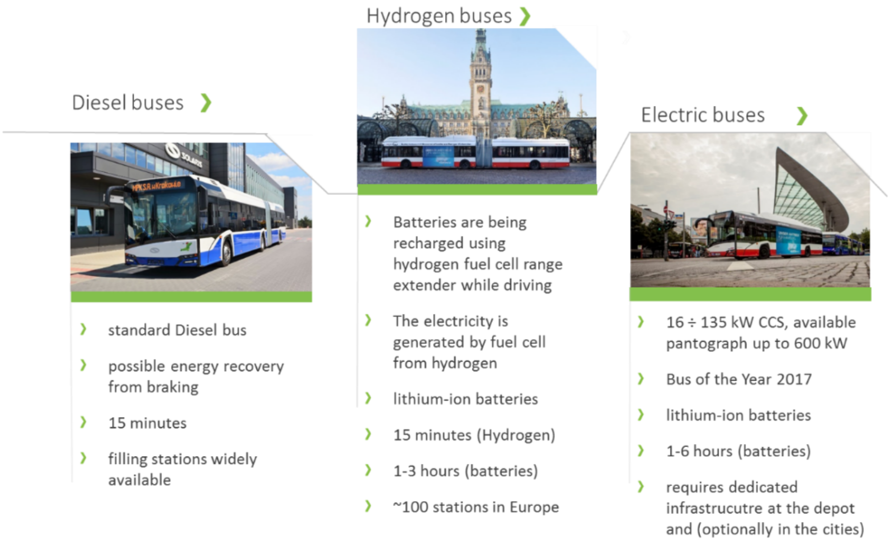



Figure 11. Comparison of Diesel, hydrogen and electric buses [4]

One of the parameters that was not mentioned in the above figure but which is very important is the mass of the bus. It is a key parameter because it defines the maximum permitted number of passengers that we can carry by bus. The mass of the bus construction including all kinds of auxiliary systems in which the bus is retrofitted by customers and air conditioning and heating systems is nearly similar, but components related to drive train (including groups Energy storage system, External/onboard power supply) shows different weights depending on the technology used.

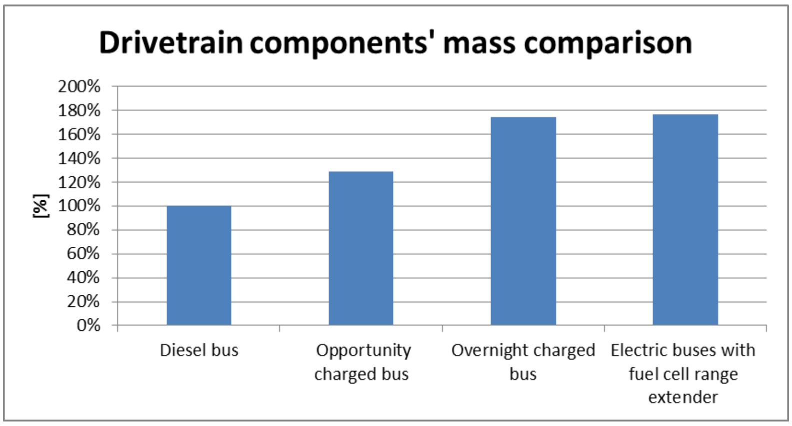



Figure 12. Drivetrain components' mass comparison [4]

At the Figure 12 are presented drivetrain components' mases. As 100% Diesel bus components were considered. To comparison presented at Figure 13 was taken Diesel bus with fuel consumption 40 l per 100 km, and electric buses with consumption of 1,31 kWh/km. Most of the customers require daily distance between 200 and 350 km, what means that the only possible way to convert a Diesel bus in to a zero emission bus if we would like refuel (recharge) only one's a day is to use a vehicle equipped with a fuel cell extender.

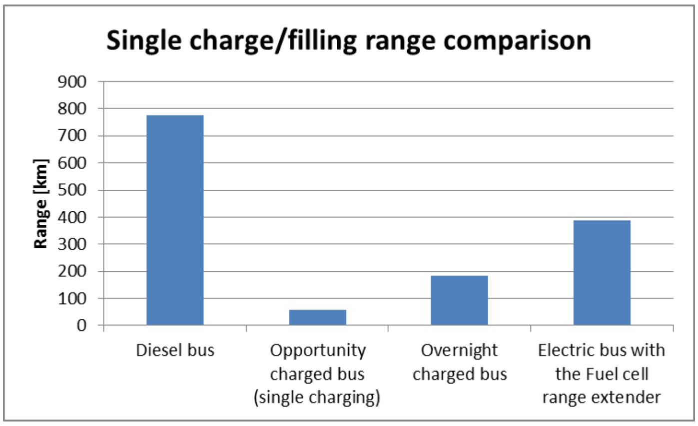



Figure 13. Single charge / filling range comparison [4]

Electric buses with the fuel cell range extenders seem to be the best solution for routes with high daily mileage and hard driving conditions. They are the only one which completely fulfill requirements for both types of urban cycles (heavy urban and mixed urban) as well as suburban for the worst conditions. They have no competitors in zero emission solution while single charging/filling range. However at this moment price for those buses is much higher comparing to standard diesel buses, and it is the most expensive option from all zero emission solutions at Figure 14.

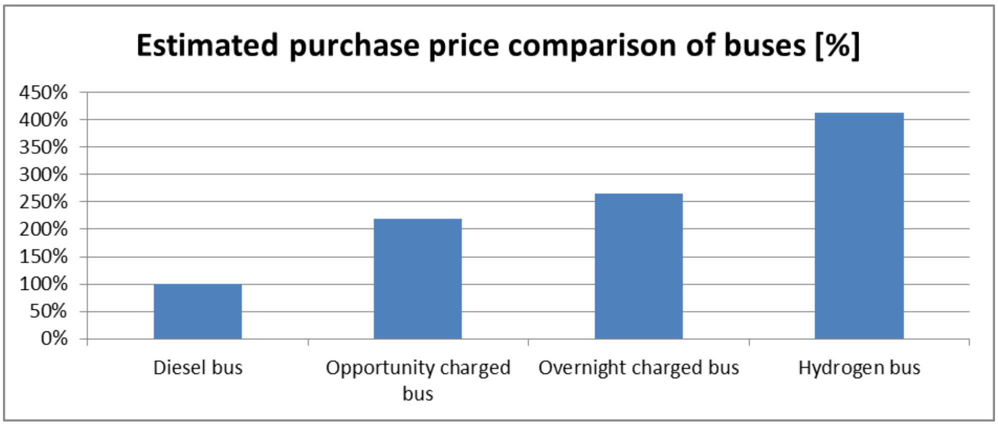



Figure 14. Estimated purchase price comparison of buses in 2017 [4]

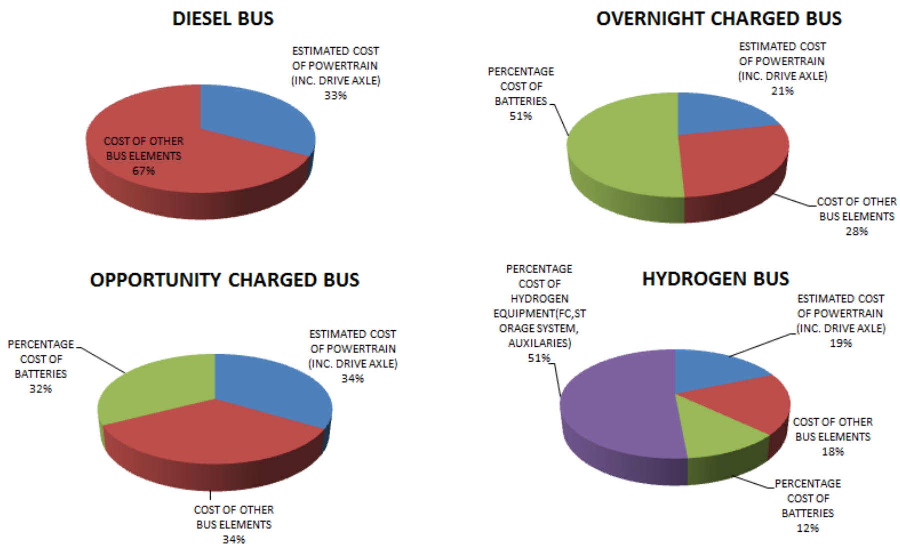



Figure 15 Comparison of costs of Diesel bus and electric buses [4]

As shown on Figure 15 the most expensive elements of electric bus with fuel cell range extender are the fuel cell and hydrogen storage system. It is expected to reduce those prices with increase of popularity of both fuel cell buses and passenger cars.

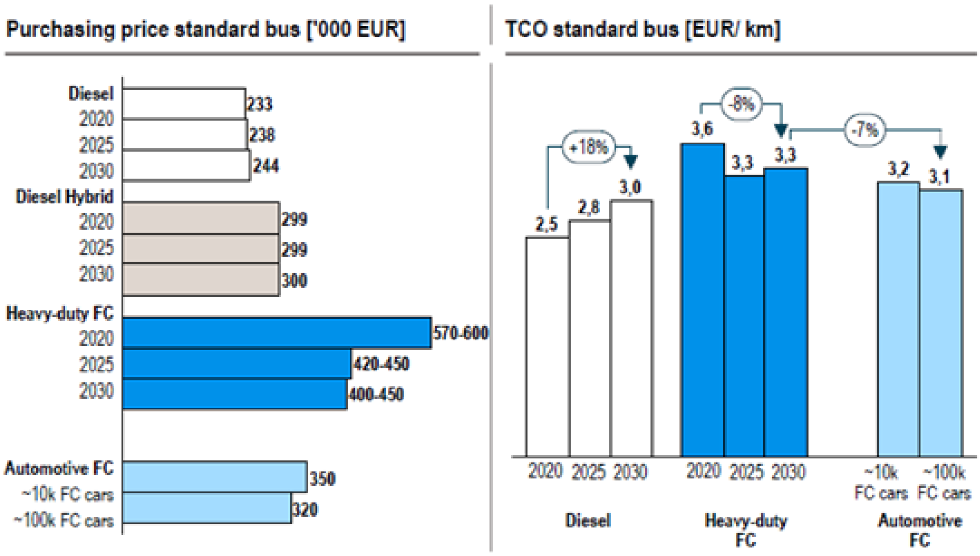



Figure 16. Analysis by Roland Berger for The Fuel Cells and Hydrogen Joint Undertaking [6]

Analysis performed by Roland Berger for The Fuel Cells and Hydrogen Joint Undertaking (Figure 16), shows bus price perspectives in upcoming years and their TCO. It is strictly connected with passenger cars' market, where number of sold vehicles needs to be higher than 10 000 units per year.

## References


[1] Deloitte Sustainability Consulting Central Europe, „Impact of Solaris Bus & Coach S.A. on economy, society and the environment,” 2017.

[2] SW Research for ORPA.pl, [Online]. Available: http://www.orpa.pl/mniej-istotna-marka-i-wyglad-lecza-sie-koszty/. [Accessed 2017].

[3] Miejskie Zakłady Autobusowe Sp. z o.o., “Autobusy elektryczne – eksploatacja w Warszawie 2015/2016,” Warszawa, 2016.

[4] Internal materials by Solaris Bus & Coach S.A.

[5] “Hydrogen Analysis Resource Center,” [Online]. Available: http://hydrogen.pnl.gov/tools/lower-and-higher-heating-values-fuels.

[6] R. Berger, The Fuel Cells and Hydrogen Join Undertaking, [Online]. Available: http://www.fch.europa.eu/sites/default/files/150909_FINAL_Bus_Study_Report_OUT_0.PDF.

# Authors

Michał Sierszyński – graduated from Poznan University of Technology at Faculty of Electrical Engineering, Automatic Control and Robotics and from Poznan University of Economics and Business - Project Management studies.

In Solaris since 2004 as Design Engineer in Electrical and Electronics Department. Since 2012 as Advanced Technology Manager in Research and Development Department.

Activities: Development, research and analysis of new technical solutions, technical project management.

Bartłomiej Walczak – received the M.Eng. degree in Mechanical Engineering from Poznan University of Technology in 2008.

In Solaris Bus & Coach since 2009. He works as a Senior Design Engineer in Bus Design Team with the background in Powertrain Team and Advanced Technologies Team. Responsible for mechanical construction of fuel cell buses, electric buses and trolleybuses, research & development.

Adam Piotrowski – graduated from Poznan University of Technology in 2016. He holds a B.Eng. in Electrical Engineering and a M.Eng. degree in Power Engineering.
Since 2014 worked in Research and Development Department of Solaris Bus & Coach, since mid of 2016 works as Junior Design Engineer in Advanced Technology Team, where he is responsible for energy consumption simulations, battery lifetime analysis, research & development.

Michał Pikuła - graduated from Poznan University of Technology in the Electrical Engineering Faculty. He holds a M.Eng. in Electric and Computer Systems in Industry and Vehicles since 2001.

In Solaris since 2001,as Design Engineer in Electrical and Electronics Department. Since 2008 Head of Bus Development and since 2014 Director of Bus Development in Research and Development Department. Responsible for supervising of engineers working on new bus constructions equipped with diesel, hybrid and electrical propulsion